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by

R.J. Celotta, D.T. Pierce and G.-C. Wang,
S.D. Bader, and G.P. Felcher

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R.J. Celotta, D.T. Pierce and G.-C. Wang
National Bureau of Standards
Washington, D. C. 20234

S.D. Bader and G.P. Felcher
Argonne National Laboratory
Argonne, IL 60439

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R.J.Celotta, D.T.Pierce and G.-C.Wang

National Bureau of Standards, Washington, D.C. 20234, U.S.A.

S.D.Bader and G.P.Felcher

Argonne National Laboratory, Argonne, Illinois 60439, U.S.A.

Abstract

A new technique, capable of observing the surface magnetization of ferromagnetic single crystals, is described. Illustrative data is presented, giving the dependence of the magnetization of the Ni(110) surface on applied field, incident energy, absorbate and coverage.

1. Introduction

The exchange interaction between an incident electron and the aligned electrons at the surface of a ferromagnet provides a direct method of determining the surface magnetization. We take as the Hamiltonian for this interaction,

$$H = \sum_i V(\bar{r}-\bar{r}_i) + \sum_i J(\bar{r}-\bar{r}_i)\ \bar{s}\cdot\bar{S}_i + H_{s-o},$$

where V and J are the Coulomb and exchange potentials respectively, $\bar{r}$ and $\bar{r}_i$ are the positions of the incident electron and i^{th} atom, $\bar{s}$ is the spin of the incident electron, $\bar{S}_i$ is the spin at the i^{th} atom site, and H_{s-o} is due to spin-orbit coupling. Using a polarized electron source to change the sign of the $s\cdot\bar{S}_i$ term by reversing the direction of $\bar{s}$, we are able to sense the net alignment of $\bar{S}_i$ at the substrate surface. The quantity we measure is $S(\bar{K})$, which is defined as the difference in the elastic scattering signal when the spins are aligned minus that when they are antiparallel, divided by the sum of these two signals for normalization. This can be calculated {1} in a simple first Born approximation to yield,

$$S(\bar{K}) = -J(\bar{K})\ M^z(T)/g\mu_B V(\bar{K})$$

where J and V are the Fourier transforms of the respective potentials and $M^z(T)$ is the magnetization per atom. Thus, our experimental determination of $S(\bar{K})$ is proportional to the magnetization, but the coefficient of proportionality and the sign depend upon the ratio $J(\bar{K})/V(\bar{K})$. It has been shown {2} that the linear relationship between $S(\bar{K})$ and $M^z(T)$ should still be approximately valid even if multiple scattering is included.

2. Apparatus

Figure 1 shows an overall view of our polarized electron scattering apparatus. The surface chamber is conventional except for its magnetic shielding. The LEED system's electron gun has been removed and electron optics has been installed to transport and collimate a beam that is produced in a polarized electron source located in an attached chamber. The NBS GaAs

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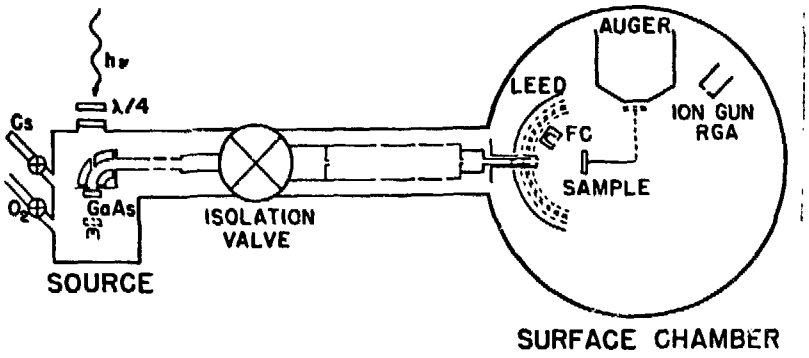

Figure 1. Schematic view of polarized electron scattering apparatus.

source {3} is based upon photoemission from a negative electron affinity surface using circularly polarized incident radiation. Modulation between right and left circularly polarized light produces a reversal of the spin direction in the 43% polarized electron beam. Currents of 20μA/mW of incident radiation are produced. The electron beam *incident* on the target crystal is of constant current with the spin direction reversed at a 30 Hz rate. Any modulation in the *scattered* beam is due to a spin dependent effect during scattering.

Alignment of the spins in the substrate must be accomplished with a minimum of stray magnetic field. In the configuration shown in Figure 2 the Ni crystal closes the magnetic circuit of a horseshoe shaped electromagnet. The [1$\bar{1}$1] crystal axis, the easy magnetization direction, is oriented along the field direction. The scattering plane is chosen to minimize any contribution due to H_{s-o}. As determined by the magneto-optic Kerr effect, the crystal can be magnetized to saturation in either direction with only insignificant deflection of a 20 eV electron beam. Heating is accomplished by passing a current through the thin crystal while monitoring the temperature with an attached thermocouple.

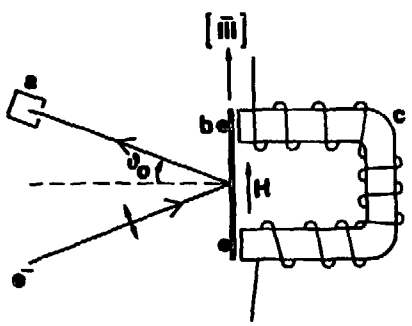

Figure 2. Magnet assembly showing Faraday cup (a), Ta support rods (b) and iron electromagnet (c).

3. Results

The first measurements made were of S and the total intensity corresponding to specular diffraction at an angle of incidence of 12°. Data were taken as a function of energy over the range of 20-150 eV. The S function for a magnetized target exhibited maxima with both the positive and negative values less the 0.05 over this range of energies. The dependence of the features upon the magnetic ordering of the substrate was tested by reversing the magnetic field direction.

From the resulting measured intensity and S variation with energy, two regions of interest were identified; at 22 eV and 125 eV. Each energy corresponded to a local maximum of the S function. Data were taken at fixed incident energy as a function of applied magnetic field. Figure 3 shows the hysteresis curves obtained. Since S, as defined, is positive if parallel spins scatter more strongly than antiparallel spins, a conventional hysteresis curve can only be obtained by choosing a preferred direction in space so that the applied fields H and -H have opposite effects. Under these conditions, the sign of S (H>0) can be seen to correspond to a reflection about the vertical axis. Hence, in Figure 3 the outer (22 eV) curve corresponds to S<0 and has an opposite sense from the inner (125 eV) curve with S>0. Both curves are symmetrically located on both axes. The x-axis scales are not the same for the two curves, but the calibrated y-axis shows the low energy effect to be a factor of 2.5 times larger.

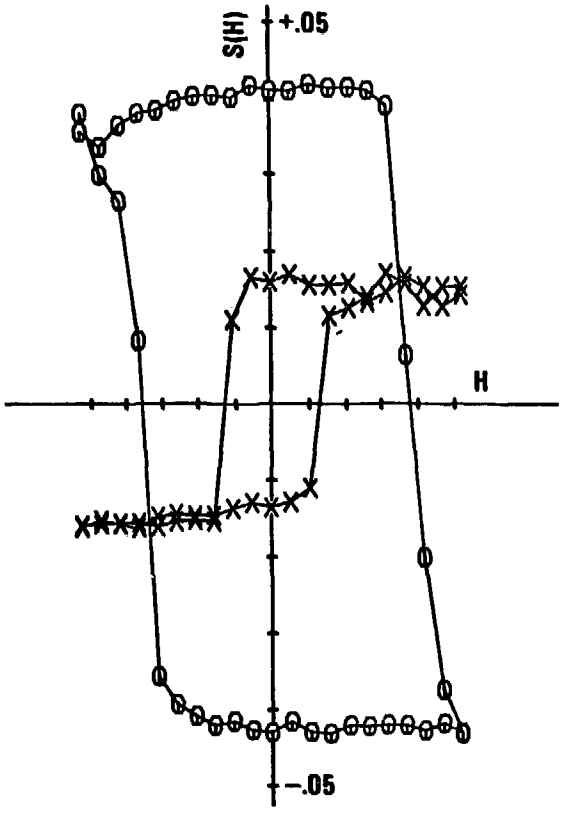

Figure 3. Hysteresis curves measured at 22 eV (outer) and 125 eV (inner).

Since the mean free path for electrons at an energy of 125 eV is 5Å these measurements are expected to represent the magnetic behavior of only the top most layers of the solid. Evidence that this is so can be seen in measurements of the temperature dependence of S. We have found {4} in the temperature range between 50% to 80% of the Curie temperature, the temperature dependence of S is approximately linear, in marked contrast with the bulk magnetization, but in agreement with theoretical expectations if the surface exchange coupling is less than that of the bulk.

The requirement that the surface be very clean before hysteresis curves can be observed is another indication of the surface sensitivity of the technique. Sulfur levels had to be reduced to ~0.03 monolayers before hysteresis curve could be obtained reliably.

In a series of controlled experiments we monitored the effect of the adsorbates H_2, CO and O_2 on the surface magnetization. Figure 4 shows the relationship between S and exposure to O_2. The S data were obtained by measuring hysteresis curves at each exposure. Also shown is a peak height ratio for oxygen and nickel Auger signals as measured using a CMA at an incident energy of 2 KV. Data were taken both by monitoring the exposure and recording S at fixed intervals and by a series of crystal cleanings and exposures to a fixed level. Similar plots were obtained for H_2 and CO exposures.

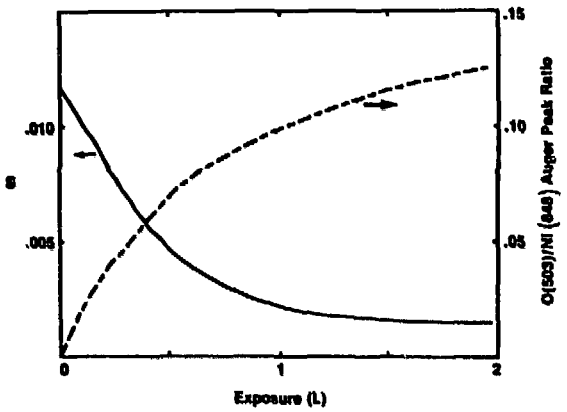

Figure 4. S plotted vs. O_2 exposure (solid curve); ratio of O (503 eV) Auger peak height to Ni (848 eV) peak height (dashed curve).

4. Summary and Future Work

We have described a new technique for observing surface magnetic phenomena and shown some initial results. Future work will concentrate on a thorough study of the temperature dependence from liquid nitrogen temperatures up to the Curie temperature as well as a detailed study of the effects of chemisorption.

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